

Swords into Plowshares: Nuclear Weapon Dismantlement, Evaluation, and Maintenance at Pantex

Edwin A. Kjeldgaard

*Sandia National Laboratories
MS-0718, Albuquerque, New Mexico, 87185-0718*

Dean A. Jones

Sandia National Laboratories

George F. List

*Department of Civil Engineering, Rensselaer
Polytechnic Institute, Troy, New York 12180*

Mark A. Turnquist

*School of Civil and Environmental Engineering
Cornell University, Ithaca, New York 14853*

James W. Angelo

Mason and Hanger Corporation

Richard D. Hopson, John Hudson

P.O. Box 30020, Amarillo, Texas 79177-0001

Terry Holeman

The end of the Cold War changed the missions of facilities in the US nuclear weapons complex. They ceased production of new weapons and focused on dismantling old weapons and maintaining the safety, security, and reliability of those remaining. The Pantex Plant, operated for the US Department of Energy (DOE) by the Mason and Hanger Corporation, is the sole assembly and disassembly facility for dismantlement, evaluation, and maintenance activities for the US nuclear stockpile. We developed a decision support tool, the Pantex Process Model (PPM), to help Pantex plan capacity and deploy resources to meet its new requirements. Using the PPM, Pantex has provided critical input to help the US form and defend positions during arms-control-treaty negotiations. It has changed the way Pantex and the DOE evaluate resource requirements in planning future workloads. It has also led to an innovative cooperative agreement among Pantex, the Transportation Safeguards Division of DOE, and the Department of Defense (DOD) that resulted in Pantex exceeding weapon-dismantlement goals.

The end of the Cold War brought new challenges to the Department of En-

ergy's nuclear weapons complex (NWC).
Production of new nuclear weapons

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stopped abruptly. International attention focused on reducing nuclear arsenals and reducing the threat of proliferation of nuclear weapons and other weapons of mass destruction. In the US, nuclear weapons production facilities were downsized (a process that continues), and the NWC became focused on dismantling nuclear weapons, essentially running the complex in reverse.

To reduce the total number of nuclear weapons, the Russians and the Americans must be sure that they are both indeed disposing of the numbers of weapons

In the nuclear weapons complex, all paths eventually lead to Pantex.

agreed to in arms-control agreements and treaties. This need resulted in treaty provisions for verification that affect operations in the NWC. At the same time, the NWC must ensure the safety, security, and reliability of the enduring stockpile.

The Pantex Plant, operated for the US Department of Energy (DOE) by the Mason and Hanger Corporation, is the facility responsible for dismantling, evaluating, and maintaining the US nuclear stockpile. It is also responsible for storing critical weapon components, which are a primary concern of US-Russian nonproliferation agreements. Pantex plays a central role in the DOE nuclear weapons production complex. In the NWC, all paths eventually lead to Pantex. Sandia, Los Alamos, and Lawrence Livermore National Laboratories are the nuclear weapon design labs. Sandia and Los Alamos also produce components that are incorporated into nuclear

weapons at Pantex, as do the Kansas City plant, Oak Ridge Y-12 plant, and the Savannah River site. The Pantex Plant currently employs about 2,850 people and has an annual operating budget of about \$288 million. Despite the very specialized nature of its operations, it has problems in common with many manufacturing facilities—making effective use of facilities and people in meeting output requirements. In its case, the outputs are those specified by US national policy and by international treaties regarding the US nuclear arsenal. Pantex must balance the requirements for dismantlement with continuing needs to evaluate, repair, and retrofit the nuclear weapons that remain in the stockpile. Furthermore, Pantex must perform its mission with fewer resources than were available during the Cold War and with ever-increasing pressure to allow foreign inspectors access to classified areas to support treaty verification.

In 1993, Pantex management recognized that the changing mission of the plant called for agility in allocating resources to evolving needs. Pantex decided to create a comprehensive planning and scheduling tool with enough scope and complexity to address all of its production activities. Sandia National Laboratories led the project as systems integrator for the NWC. Sandia assembled a team composed of Sandia staff, Cornell University and Rensselaer Polytechnic Institute faculty, and Pantex production planning and scheduling department staff.

The team developed the Pantex Process Model (PPM). The PPM contains a set of optimization modules, coupled with a tightly integrated set of Pantex databases.

The model's modules are capable of analyses over vastly different time horizons for planning resource requirements and using resources optimally. The PPM includes sophisticated user interfaces (including geographic-information-system capabilities), a fully relational database, and analysis modules and optimization engines focused on planning short-term dismantlements, scheduling short-term evaluations, and planning long-term plant resources. Since its implementation, the PPM has become the primary tool for analyzing planning and scheduling issues at Pantex.

Problem Definition

The PPM is an optimization system designed to guide Pantex managers in allocating resources among competing demands, all of which are important. The PPM is designed to answer a variety of questions over varying time horizons, for example the following:

- How will a proposed treaty stipulation affect Pantex's ability to accomplish its tasks, and what recommendation should it make to US negotiators on this proposal?
- How will treaty verification activities affect Pantex operations?
- Does Pantex have the resources to meet the requirements of proposed treaty agreements?
- How rapidly can Pantex dismantle the weapons of a particular type, given its other responsibilities?
- Does Pantex have enough staging facilities for incoming weapons and storage areas for parts from dismantled weapons?
- Has Pantex trained enough technicians to run a planned dismantlement program?

Answering these questions requires analyses covering time periods ranging from a few months to many years.

Dismantling retired weapons and evaluating the remaining weapons draw on the same facility and technician resources. An effective production-planning model must deal with this resource contention. However, the two activities differ in structure and must be modeled differently. Dismantlement is like a disassembly line, with a series of weapons of the same type proceeding through the same sequence of operations. Each operation requires a specific facility and technicians with a particular certification. In modeling dismantlement, we focus on the flow rates of weapons of various types through the system, and on the rate of consumption of resources (for example, facility-hours and person-hours).

In contrast, evaluations are performed on individual weapons sampled from the enduring stockpile. Each evaluation is somewhat different; the sampled weapons are processed one at a time. Individual weapons are disassembled, tested, and reassembled in predetermined ways. Pantex must track these units and assign resources for specific tasks. Precedence is important, and some tasks can be done in parallel. Due dates are common for intermediate tasks (for example, a particular test step) and deadlines are rigid. Some tasks have higher priority than others because of constraints imposed by external entities, for example, the Department of Defense (DOD).

Allocating technicians and facilities is complicated by the demanding, complex rules for safety and security. Technician-

allocation considerations include the following:

- Before technicians can perform a particular operation, they must be trained and certified for that operation. Each technician holds up to five certifications. Allocating some 300 technicians and 100 unique certifications is daunting. Also, these certifications must be used or they are lost, as determined by other complex rules. Retraining technicians is costly and time consuming, and it affects production capacity.
- Most operations require at least two technicians, both holding the same certification. In many cases, operations require crews of four.
- Pantex must follow strict guidelines to ensure that technicians receive radiation doses as low as reasonably attainable. If they reach the maximum dose level, they are unavailable for production activities for a specified period of time, regardless of their certification status.

Facilities are also allocated according to complex rules for safety and security. The model covers 82 production facilities, categorized into 29 facility types. Each facility type is governed by a set of rules, including limits on quantities of fissile and explosive materials and environmental and physical stipulations. Furthermore, a hierarchy exists, so that operations normally performed in a type A facility can also be performed in a type B facility, but the converse is not true.

An additional complicating factor is that Pantex has limited storage capacity in magazines used to store weapons and parts removed from the weapons. Use of the storage facilities is governed by complex rules for safety and security. Because

of storage (or staging) constraints, the arrival, staging, and shipment of weapons, and the storage, staging, and shipment of parts must be closely monitored and controlled to support a production plan and schedule. Currently, the PPM tracks arrival, shipment, and storage quantities for 55 parts.

PPM Architecture

Conceptually, it is possible to formulate the PPM as a very large mixed-integer-programming (MIP) problem [Kjeldgaard et al. 1998]. However, a typical problem instance of this formulation would have about 50,000 integer variables. Solving this MIP directly is not feasible. For example, in an early experiment, we tried to solve a small test problem (with 26 evaluation tasks and only one severely constrained resource) to optimality using a commercial linear-program/integer-program/mixed-integer-program (LP/IP/MIP) solver. After about two hours of computation on a PC, we terminated the run without finding an optimal solution. As PC capabilities continue to improve, it is possible to solve problems of increasing size, but this experiment convinced us that we were very far away from being able to solve the real problems at Pantex using brute-force MIP solvers. We approached the problem in a different way. We decomposed the problem into modules (Figure 2). The three main modules of the PPM are tied to a Microsoft Access database, which is integrated with a set of networked Pantex databases. All necessary modeling data is stored in an Access database, which is connected to multiple Pantex databases via a secure network. The main modules are the disposal-planning module (DPM),

the evaluation-planning module (EPM), and the long-range-production-planning module (LRPPM).

The Disposal Planning Module

The DPM is a large-scale linear-programming model. It seeks to maximize the total number of units (weapons) dismantled over a one-year planning period, subject to constraints on the availability of facilities, technicians, and space for storing and staging incoming units and outgoing parts or subassemblies and subject to mandated program requirements for specific weapon types. A typical problem instance has approximately 2,000 variables and 2,000 constraints.

The DPM's output is an optimal monthly disposal plan for a one-year period. Shadow prices, slack variables, right-hand-side ranging results, and other LP outputs provide further sensitivity information useful in adjusting the plan. In addition, binding constraints identify the choke points and enable Pantex to prepare long-term resource-investment plans. Moreover, the outputs are graphical, which helps the production-planning-and-scheduling staff to communicate their findings to other decision makers.

The Evaluation Planning Module

The EPM formulation is similar to a resource-constrained project-scheduling problem (Appendix). The EPM creates a plan for conducting prespecified stockpile-evaluation activities over a one-year period. Typically, each evaluation involves an earliest possible start time, a due date for completion, and a specified set of tasks to be performed in a particular order. Each task requires a certain type of facility and technicians with a specific certifica-

tion. The EPM output is a schedule-like plan, at a weekly granularity, indicating when specific tasks should be done and the facilities and technicians required.

By the standards in the literature on scheduling theory (either job-shop scheduling or project scheduling), the EPM is also a very large problem, with several hundred jobs, more than 1,000 tasks, more than 20 facility types, and more than 100

Dismantlement is like a disassembly line.

technician types (certifications). The size and complicated nature of the problem dictate that we use heuristics to find good (not necessarily optimal) solutions. Our approach to solving the EPM problem is based on using a nonlinear approximation to an underlying mixed-integer-programming model. We solve this nonlinear problem using a sequence of linear-programming problems to generate implementable solutions. Comparisons with optimal solutions for small test problems indicates the solution strategy works very well (Appendix).

Long-Range Production-Planning Module

The LRPPM is a large-scale linear-programming model (Appendix). It produces a long-term (up to 30-year) production plan that encompasses dismantlement, evaluation, and life-extension program activities. Because the US is no longer producing new nuclear weapons, life-extension programs (LEPs) are intended to extend the longevity of weapon systems. LEPs will make up much of Pantex's workload in years to come.

The effects of treaty obligations often play out over several years, and the LRPPM is a critical element of Pantex’s participation in forming the US positions in treaty negotiations. Pantex uses the LRPPM to project total resource requirements over multiple years and to determine if potential workloads will be feasible.

The LRPPM also provides input for Pantex’s long-term site plan, which includes projected facility investments and staffing levels for 10 years or more.

We formulated the model as an LP, using months as the basic time period (Appendix). We derived input data from the same databases we used for the shorter-term DPM and EPM (Figure 1), but the

level of detail is not as high. A typical problem instance has about 15,000 variables and about 14,000 constraints.

Summary

The PPM integrates dismantlement and evaluation activities into a single unified framework, with the two activities competing for common resources. Together, the modules of the PPM provide guidance for allocating these resources.

The PPM has several innovative features. Most significant is the multi-time-scale nature of the analysis modules, which operate off the same underlying database and data structure. Short-term analyses are very detailed, while long-range analyses are macroscopic. The solutions are consistent because the models and underlying data are consistent. Second, although dismantlement and evaluation activities differ in structure, they are planned in an integrated fashion, working with shared resources and a common database. Short run, the EPM and DPM inform resource divisions between dismantlement and evaluation activities. Shadow prices and pseudo resource deployments suggest whether these divisions are optimal or not. At the macro level, the LRPPM also informs these short-run resource divisions, and long term, it guides total resource investments. Third, the model explicitly considers hierarchical resource substitutions, varying penalties for violations of resource availability, and connections between production planning and material-flow management.

Software Environment

We used a PC platform running under Windows 95 or NT to implement the PPM because this is the operating environment

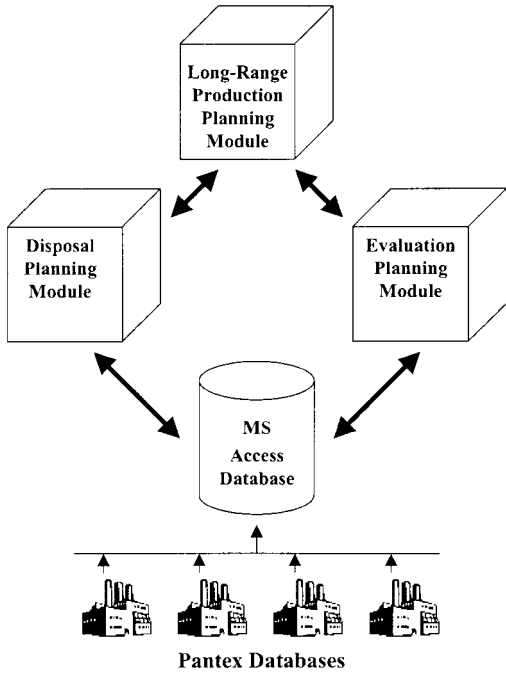


Figure 1: The long- and short-term planning capabilities of the PPM are integrated. All necessary modeling data is stored in an Access database, which is connected to multiple Pantex databases via a secure network.

at the plant. The model uses an object-oriented design in which the graphical interface, analysis modules, and data-handling functions are crafted in Visual Basic 5. We used Microsoft Access as the database management system, which allows integration with other Pantex database systems. We maintain full integration with Microsoft Project and other Microsoft Office tools, specifically Excel, Word, and PowerPoint, using ActiveX and OLE technology. The analysis solvers employ two commercial solvers, LINGO and CPLEX to solve problems. We chose these elements because of the PC desktop environment and the need for agility, rapid prototyping, and ease of use. We maintain real-time network connections with the plant's information network to acquire data and to disseminate results.

Development and Implementation of the PPM

Important to the success of the PPM development effort was including model builders, software developers, and end users in a cohesive team. This aided frequent iterations in the development cycle, leading from early prototypes to final products. We repeated a cycle of goal setting, development, testing, and refinement, sometimes referred to as spiral development, several times. Typically, the team defined and discussed a problem and proposed an initial analytical approach. The development team then created a mathematical formulation that addressed the problem. We then prototyped and reviewed the formulation with Pantex management. Once we confirmed that the formulation was addressing the problem correctly, we developed a beta version of

the software and delivered it to Pantex, where the staff of the production planning and scheduling department helped test the software. This ensured that they could obtain solutions to current problems and that the new features were functioning as desired. As needed, we modified the formulation in response to test results. When all issues were resolved, the new application was implemented.

During this collaboration, we emphasized agility and flexibility. The development team's objective was to maximize the PPM's ability to change and evolve in response to internal (Pantex) requirements or external requirements. As they gained insight into the capabilities of the PPM, the Pantex team members became its consistent and effective champions. They could show how the PPM, as it evolved, was useful in addressing critical problems at the plant, and they could provide credible analysis results to support managerial decision making. As we developed crucial solution strategies with the PPM, upper management became convinced of the value and accuracy of the analyses. Pantex management, as well as DOE, gained confidence in the solutions and began to rely on the results. Conversely, through this same close working relationship, the Sandia and university members of the development team gained crucial insight into Pantex's operational requirements.

Since the PPM can analyze varying time resolutions, Pantex personnel use it in several different ways. Schedulers use it for detailed capacity-requirements planning every day while planners use it for long-range capacity planning once a month (Figure 2). The PPM is the primary tool

analysts use. The planning process begins with requirements set forth in several DOE planning documents. These high-level requirements are based on agreements between DOE and DOD. Using the PPM, Pantex planners turn these requirements into a resource-constrained-capacity workload plan that managers use to determine whether Pantex will commit to the proposed workload. If the results indicate a resource constraint, they use the PPM to determine what change in resources is needed. Program managers, directors, and division managers at Pantex use PPM results to support their decisions.

Impact at Pantex

The PPM has contributed to Pantex’s success in three areas: (1) support of nuclear-weapons-treaty negotiations between the United States and Russia; (2) changing the way that Pantex and DOE measure workload and resource requirements at the plant; and (3) exceeding weapon-dismantlement goals for FY1998. In addition, Pantex managers have demonstrated their commitment to the long-term use of the PPM by changing the structure of the organization, emphasizing the PPM and the personnel supporting its use as a key factor in the mission of the

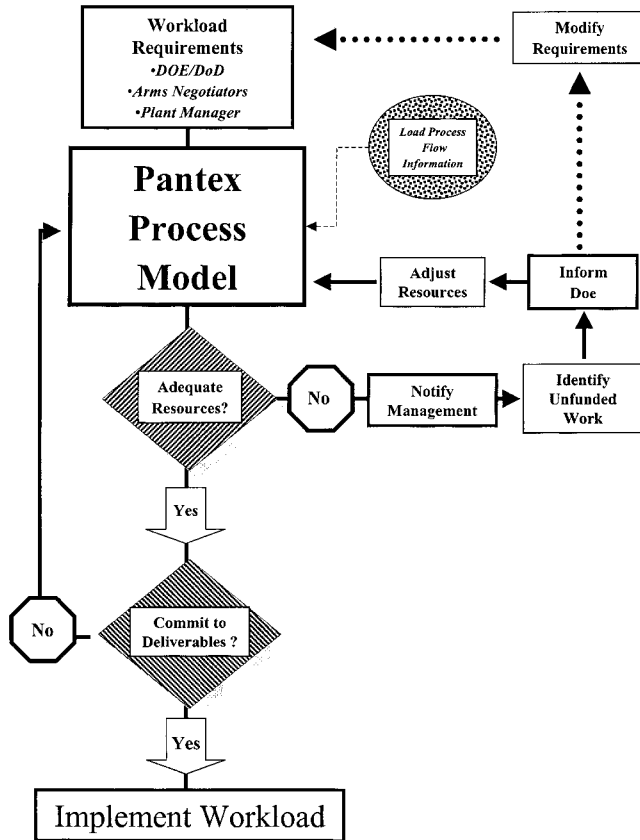


Figure 2: This diagram of the information flow and the use of the PPM shows how the PPM is used to support long-term workload decisions. This includes analyzing, verifying, and committing to future workloads, based on internal and external requirements.

company.

As a result of the credibility of the PPM analysis, DOE headquarters now relies on PPM information to support the US position in treaty negotiations. Over the past two years, Pantex has made extensive use of the PPM to investigate future dismantlement capacities and future stockpile-support activities consistent with potential treaty provisions. DOE headquarters used the resulting information to recommend positions in the negotiations the Department of State was conducting. Ambassador Paul Robinson, president and director of Sandia National Laboratories, who served as the US negotiator for the nuclear testing talks in Geneva from 1988–1990 summarized the importance of this capability at the INFORMS spring national meeting in Cincinnati, Ohio on May 2, 1999: “We constantly faced the issue of how to incorporate arms control constraints without bringing to a halt critical operations of our defense community . . . [the PPM] has made it possible to test out the impact of new verification ideas before they are locked down in treaty language.”

The graphical results of the PPM (Figure 3) support treaty negotiations. Bill Weinreich, Pantex Plant general manager, stated at the INFORMS meeting: “anytime I’m asked to testify before Congress or asked questions by Congress relative to our needs, I take [these charts].” These charts show the projected requirements for facilities and production technicians at Pantex out to 2025. The calculations are based on projected weapon quantities related to anticipated US treaties and dismantlement, evaluation, and maintenance

activities. The workload derived from US disarmament agreements must not negatively impact the safety, security, and reliability evaluations of the remaining stockpile. With the PPM, we can calculate the entire projected workload for Pantex, which must satisfy many national policy needs simultaneously. With the PPM, analysts at Pantex can prepare various alternatives for officials at the DOE, the DOD, and the Department of State.

With the PPM, we can calculate the entire project workload.

The projected facility requirements are fairly stable from FY1998 through FY2003, with adequate facilities available using a single shift (Figure 3). They dip during FY2004 when a particular type of workload is to come to an end. From FY2007 until FY2020, the projected facility requirements could not be met even with a second shift. For the US to meet its strategic nuclear-deterrent goals, Pantex must increase its facility capacity. This type of result motivates Pantex to refurbish or obtain new facilities. Since the lead-time for a new facility can be from six to ten years, this information is invaluable for determining future budget requests.

The projected demand for production technicians over the same period of time varies from year to year because different weapons systems vary in difficulty and, consequently, in processing times (Figure 4). The projected additional demand for technicians between FY2005 and FY2009 is due to a proposed disarmament agreement between the US and Russia. With

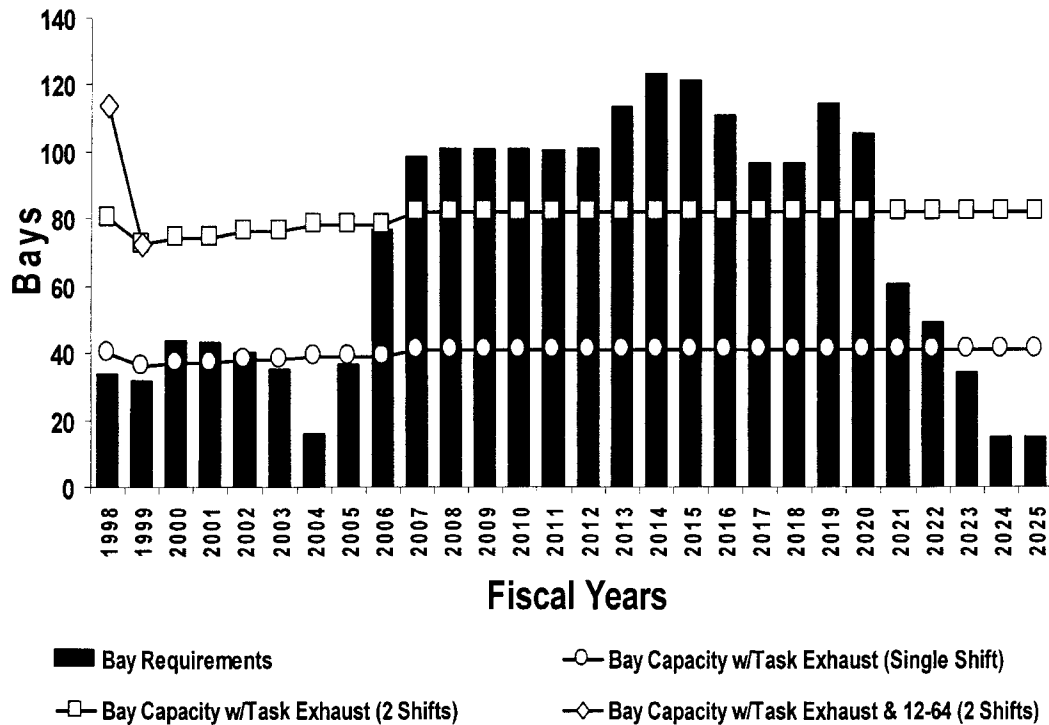


Figure 3: The demand for weapons operations bays is based on the overall workload, including treaty-related work. The two lines indicate single- and double-shift capacity per fiscal year. These requirements are based on the entire anticipated workload.

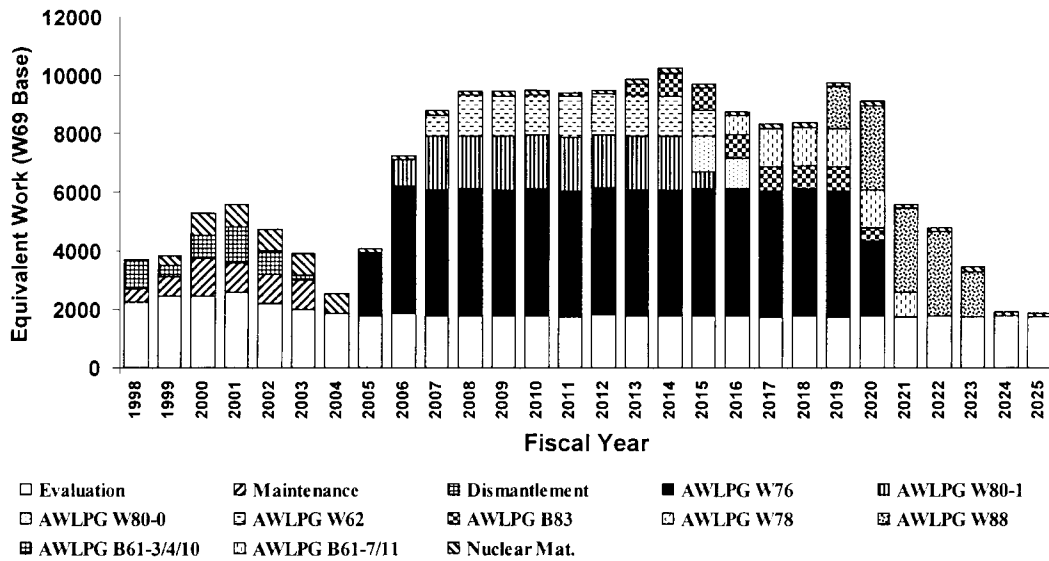


Figure 4: The demand for production technicians by workload type varies over a 28-year period.

this information, the US can determine how to respond to these competing demands. For example, Pantex could hire and train additional technicians (with a lead time of two years), as calculated by the PPM, or Pantex could use the PPM to level the workload from year to year while considering the hard constraints of the US-Russian treaty agreements.

The tremendous value of the PPM in supporting arms-treaty negotiations is best summarized by Gene Ives, the DOE deputy assistant secretary for military application and stockpile management. He is responsible for carrying out DOE's responsibilities to achieve the national security objectives established by the president of the United States. He is also responsible for maintaining the stockpile of nuclear weapons. Ives stated at the 1999 INFORMS spring national meeting that, "information from the model allows me to talk confidently with officials at the Department of Defense and the Department of State about how we can continue to maintain our nuclear deterrent, while preparing for negotiations with Russia on warhead reductions."

The PPM's second major area of impact is in changing the way that DOE and Pantex relate to one another and the way they measure workload and resource requirements—using resource requirements instead of weapon quantities. With the PPM, Pantex has a mechanism to evaluate resources (technicians, facilities, and storage and staging areas) needed to accomplish a workload composed of various types of dismantlement, evaluation, and life-extension activities. The PPM has given both Pantex and DOE a much-improved

basis for evaluating workloads. Prior to PPM implementation, DOE measured workload simply by numbers of units dismantled or evaluated, which failed to reflect the fact that resources required per unit vary widely across weapon types. These estimates required several people to put in weeks of effort and resulted in an answer, not the best answer. With the PPM, Pantex can analyze specific resource requirements much more accurately and can demonstrate that it is allocating resources optimally to meet the workload. This has led to a completely new way of measuring capacity throughout the NWC according to the capacity of available or proposed resources, whether they are facilities, qualified personnel, staging space, or budget. As a result, Pantex was able to justify and obtain \$20 million in additional funds to handle the predicted workload in FY1999.

Based upon the PPM's predictions, Pantex gained DOE support to modify existing facilities or construct new buildings to meet future needs. It will need at least \$17 million to modify an existing facility, and perhaps as much as \$70 million to build a new facility, to remedy projected capacity shortfalls in key production facilities beginning in 2006. Pantex has submitted the proposal and the supporting information provided by the PPM to DOE for review. DOE agrees that one of these options must be implemented. The final decision is still pending. This example shows the power of the PPM. Prior to its implementation, Pantex, and ultimately DOE, could not determine whether sufficient manufacturing capacity existed for future work. With the PPM's results, Pantex identified two feasi-

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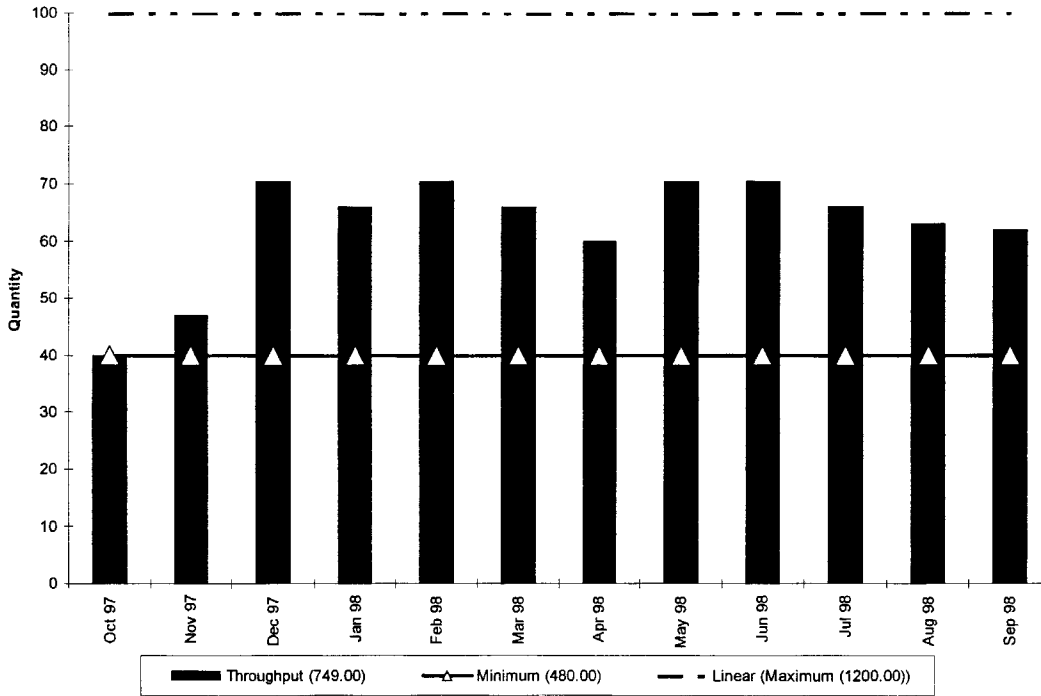


Figure 5: In these throughput results from the PPM that exceed minimum requirements on a monthly basis for a particular weapon system (W69), the maximum represents weapon arrival limitations and limits on acceptable resource dedication, and the minimum is based on DOE requirements for dismantlement throughput.

ble alternatives. Pantex has incorporated these types of results into its 10-year site plan, which outlines the resources needed to meet DOE’s projected workload. Pantex’s 10-year site plan has been adopted as the model for the rest of the nuclear weapon complex’s sites to emulate. The PPM’s output is a key constituent of this long-range plan.

The PPM’s third major impact was enabling Pantex to exceed one-year weapon-dismantlement goals for FY1998 for the W69 warhead (Figure 5). In the first month of the year, Pantex met DOE’s minimum requirement. PPM analysis indicated, however, that additional through-

put was possible in subsequent months. The throughput varied from month to month because of what resources were available and the number of production workdays per month, but it always exceeded the DOE requirement. Using the PPM, Pantex determined that the arrival rates of weapons from the DOE Transportation Safeguards Division (DOE/TSD) constrained its production. Pantex also used the PPM to assess potential problems with inventory of the weapon and with the plutonium staging space needed to support the increase in production. The PPM helped Pantex to determine the rate-limiting resource and allowed decision

makers to see a way to commit to the goal of increasing throughput. The results of the PPM analysis provided the basis for an innovative agreement among Pantex, the DOE/TSD, and the DOD to increase dismantlement throughput. Because of the sustained increase in throughput capability, Pantex finished the W69 dismantlement program ahead of time and received formal commendation from DOE. In addition, Pantex exceeded the expectations related to the W69 program in its award fee-based contract. This type of contract outlines required levels of performance and the monetary reward for completing the work on or ahead of time.

Conclusions

With the PPM, Pantex can plan current and future production resources to meet mission requirements. Pantex can provide timely, credible planning information to support decisions at the highest levels of the US government regarding treaty negotiations, dismantlement, and long-range planning for nuclear-weapon-stockpile stewardship. Treaty negotiators can now commit to treaty language knowing the direct impact their decisions will have on Pantex operations and US national policy.

The PPM has also changed the way Pantex and DOE view production planning. Since resource capacity can now be modeled, it, rather than workload, has become the measurement for funding across the NWC. The PPM enables Pantex's production planning and scheduling department to respond rapidly and accurately to what-if inquiries from both Pantex management and DOE, and it allows development of

optimal plans for reallocation of resources. In the post-cold-war environment, Pantex's mission is changing, and it relies on the flexibility the PPM offers to analyze short-term and long-term planning and scheduling scenarios.

Secretary of Energy Bill Richardson, at the 1999 INFORMS spring national meeting, summed up the value of the PPM in these words: "I am pleased to recognize that the collaboration among Pantex, Sandia, Cornell, and RPI has developed a product that is having high impact on the Department of Energy. The Pantex Process Model is not only increasing the efficiency of the nuclear weapons complex, but it is also proving to be a valuable tool in the efforts of our government to significantly reduce the global nuclear danger."

Because of the experience it gained in developing the PPM, Sandia National Laboratories has launched additional research efforts. It hopes to develop improved solution methods for EPM-like problems; this type of planning and scheduling need is common in other parts of the NWC and in nondefense applications. It also aims to develop tools for analyzing and enhancing production surety—making resource-allocation decisions that are robust under various uncertain conditions and allowing NWC managers to understand levels of confidence in meeting mission objectives. Sandia expects the research to benefit Pantex and other NWC sites.

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